Chapter 8
Transportation and Routing

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8.1 Introduction

Transportation plays a vital role in forest operations. As a fraction of total procurement costs, transportation can be as high as 45 %, which is the case in Chile. Corresponding numbers in other countries are Canada 36 %, Australia 18–25 %, Southern US 25–35 %, Sweden 30–40 % and New Zealand 40 % (Audy et al. 2012a). The characteristics of transportation depend significantly on the type of forest and managements as well forest ownership state. For example, in US and Canada a significant percentage of forests are native, where road building and maintenance plays an important role, and operational transportation costs are less important. In plantations, which are usually closer to existing roads, transportation costs play a larger role. Such is the case in countries like New Zealand, Chile, South Africa and Southern US. In Sweden, the forest ownership characteristics play a role. The existence of many small owners leads to a different form of transportation, as will be shown.

The main element in transportation is to move timber (or logs, round-wood) from the forest to first destination, usually a mill: pulp, paper, sawmill, or energy. In

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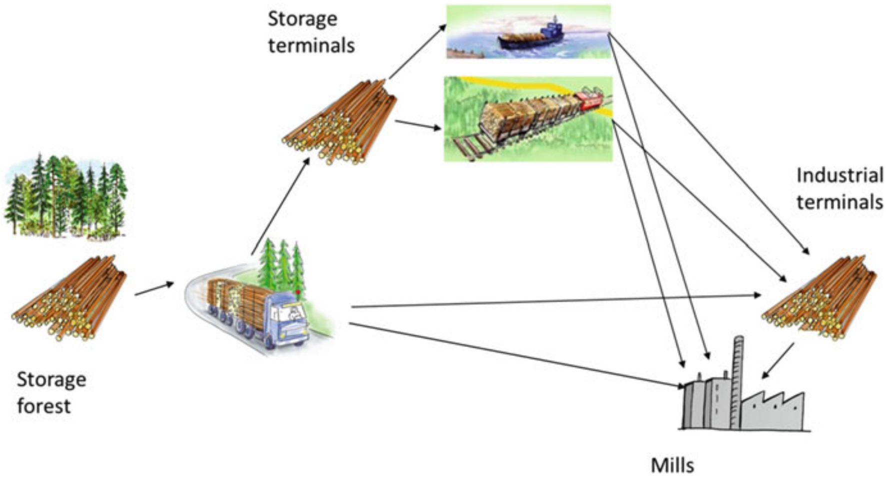

Fig. 8.1 Illustration of the main transport of timber from forest to storage facilities or mills using trucks, trains and vessels (from Rönnqvist (2012))

other cases it can be a port for direct export, or a terminal, where timber will be stored for later use. Moreover, there may also be storage possibilities close to the mills. The main transportation is by different truck types but train multimodal systems and vessels are also important transport modes, in particular for longer distances and large volumes. When no transportation infrastructure exist for such multimodal systems, truck multimodal systems combining heavy-load trucks (e.g. up to 165 ton payload in Canada) for upstream transshipment point flow and standard ones for downstream flow can take place. Most systems developed deal with this type of transportation which is illustrated in Fig. 8.1. But we also need to consider transportation from primary destination to secondary ones, for example, from sawmill to clients or to secondary manufacturing plants.

We consider different levels of planning. At strategic level decisions are made over up to 5–10 years on the transportation mode to be used and its network infrastructure system. Typical decision involves location of terminals, primary road network and selection of transportation mode (including multimodal system). At tactical level decisions involve planning for a year, a season or a month. For the longer horizon, for example one year, the number of trucks per truck type can be considered a tactical decision. How many trucks will be contracted for the next year is a typical example in Chile. Here truck assignment models are used to estimate the need for trucks. On the shorter horizon, e.g. one month, the truck fleet is assumed fixed and there is a given industrial demand to satisfy each time period. Several models developed in this area have been carried out in the Scandinavian countries. The models are used to determine the allocation from supply areas to industries taking into account backhauling flows. Where OR models have been most prominent is at operational level, where the actual routing of vehicles is carried out. On this level, any use of train system and vessels are considered to be given supply and demand points in the network. A fourth level is real-time decisions and essentially

concern truck dispatching, i.e. the assignment of the next load (or more) to a truck as the transportation operations occur.

Most models developed show the use of trucks in carrying timber from origins at the forests to destinations. Decisions here involve which origins are served by which trucks and the routing of the vehicles. We will show successful applications in Chile, Brazil, South Africa, New Zealand, Sweden, where systems have been developed to consider these problems. The approaches have included heuristics, simulation and exact mixed integer formulations, solved approximately in most cases.

Ideally transportation decisions should be taken jointly with harvest operation decisions and integrated into the whole value chain from forests to final customers. This important issue has been discussed earlier in Chap. 7 and we refer to Table 7.1 for different integration problems. We will discuss this integration in this chapter. There is considerable interest worldwide in finding ways toward cost-savings opportunities in transportation (Murphy 2003), including making transportation operations more efficient with better planning. Fuel cost representing a significant proportion of transportation costs, volatile crude oil world markets and growing environmental concerns (i.e. greenhouse gases emissions reduction) are also drivers to improve transportation efficiency. In addition, when using many trucks, there is a desire to balance the workload such that all truck drivers receive a fair share of the overall work load. This means that there often is a multi-objective goal to consider in the planning process.

What You Will Learn in This Chapter

- Distinguish between strategic and tactical/operational transportation/routing
- Understand strategic transportation models and related solution methods.
- Understand tactical transportation models and related solution methods.
- Understand routing and operational models and related solution methods.
- Provide examples of transportation and routing applications encountered in the literature
- Have knowledge about open research topics that may inspire future work in this domain

The remaining chapter unfolds as follows. Section 8.2 describes the network and information needed for all transportation. Sections 8.3 and 8.4 focus on strategic and tactical transportation problems, respectively. Section 8.5 describes routing models and methods, and Sect. 8.6 focus on the wood reception planning. The chapter ends with a discussion of open questions and future research directions in Sect. 8.7, a summary in Sect. 8.8, and finally, some problems are presented in Sect. 8.9.

8.2 Network Structure

We present the problem in the form of the value chain that spans from harvest areas to final destinations with deliveries of final products to customers. The value chain can be viewed in a network representation where the nodes represent physical

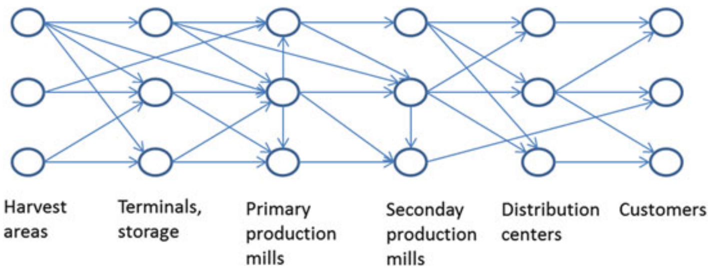

Fig. 8.2 Illustration of a general network representing the value chain

entities where activities are carried out, and the arcs represent transportation in different forms. Figure 8.2 shows a schematic form of a value chain that includes forests, where harvesting will be carried out, terminal and storing areas, where timber will be stored for a period of time, different plants, including pulp and paper plants which are major investments and play a large role in the industry, sawmills, secondary plants like panel mills, energy plants which receive residues as well as low quality timber in some cases, ports or other embarkation sites, and final customers of the different products. We will concentrate in particular on the arcs linking the nodes, which will represent the different forms of transportation. According to the type of decisions made the network will take different forms. At strategic level the types of nodes (plants for example) and arcs (transportation mode) are part of the decision process. At tactical level the network is basically fixed, and decisions involve the flows along the network. At operational level, it is more routes and sequences of arc use that are the decision variables. As mentioned, at all levels there is important interaction between the nodes (production) and arcs (transportation).

In the next sections, we describe a number of decisions at strategic, tactical and operational level. We will see how the basic structure of the network in Fig. 8.2 is preserved and how at different planning levels there are significant variations on the relevant part of the network depending on the decisions to be taken, and the information that will be needed. In these sections, we present different models that have been proposed and used, as well as what data is needed. For the network, it is important to have necessary information regarding the transportation infrastructure. For instance, on the roads network this includes road distance, road quality, road width, road slopes, speed limits etc. All this is needed in order to compute accurate distance or travel time between nodes in the network (Flisberg et al. 2012) and to compute upgrading costs to improve the road quality (Frisk et al. 2006). Here, Geographical Information Systems (GIS) are very important. At the same time, it can be costly and highly resource consuming to both collect and maintain this information with a high quality.

8.3 Strategic Transportation Planning

Both at strategic and tactical planning, forest transportation can be either separated or integrated with harvesting. If we study Fig. 8.2 showing the value chain, we can identify the strategic decisions related to harvesting and timber transportation activities. At the strategic level, the problem is not defined in high spatial detail and data are highly aggregated. The first nodes correspond to harvesting in the forest. At strategic level main decisions involve long range level of harvesting and silvicultural practices, replanting with different options, and also purchase of timber lands. At this level, the nodes correspond typically to 'macro stands', that is areas which are silviculturaly similar and geographically close and thus can be grouped together for management treatment (but not geographically identified). Spatial identification is carried out at tactical level.

The second set of nodes corresponds to plants at primary level. At strategic level we will be concerned with decisions involving major investments, in particular pulp and paper plants, but also sawmills and other plants. Pulp and paper plants need to be identified spatially, whereas smaller scale investments can be defined with less spatial detail. The third set of nodes indicates secondary plants, like panel mills, while the fourth corresponds to final customers. The arcs of the network correspond to the transportation part of the value chain. While construction of major roads can be defined explicitly, most road building need not be defined in spatial detail at strategic level. As described in Weintraub and Cholacky (1991), at this level of decisions, the plans for road building can be described in a more general way, indicating a level of investment and connectivity. Collection of information and data is not trivial at strategic level, given the long range horizons considered and the large amount of data. Uncertainty plays a major role, in particular in long range market conditions. Obtaining robust solutions is important and this is discussed later in this section. We present a simplified deterministic strategic planning model. Note that this model is one of many possible versions. Given the investments involved, the length of a rotation (in Chile) might be a minimum span of 40 years or more.

As described earlier, 'macro stands' will be defined for the model. Each macro stand will be composed of multiple basic stands, forming a non-compact area, but in a geographically close neighborhood to consider transportation costs. To describe the timber production, growth models are used separately to determine the volumes of timber obtained per hectare and species when harvesting in any period. At this level no detailed description of timber type, such as lengths and diameters is normally used. Both investments costs and operating costs are considered. These involve the management of timber lands, the different types of plants, where investment and processing costs need be defined, transportation where investments in road building or upgrading, fleet acquisition of trucks, (or other means of transportation) and hauling costs need be considered. The objective has revenues due to sales of timber and products. The production at plants, capacities, processes and costs at each plant need to be defined. To simplify the model, we make several assumptions. We consider only one level on plants, transportation between macro stands and plants can be defined through one road that either exists or needs to

be built. We neither consider land acquisition nor complex silvicultural separate alternatives, to concentrate in the transportation part of the problem. We consider plants decisions as already taken. In reality, given the importance of location to consider road building and transportation costs decisions on investment in plants, land acquisition and major silvicultural policies should be considered integrated to strategic transportation planning. We do not include in the model considerations on environmental preservation and sustainability, which are clearly major issues (Weintraub et al. 2000). We consider one type of timber but several wood products.

A deterministic model assumes the data is correct and no uncertainty takes place. In long range models this assumption will clearly not be true. Not much has been developed to obtain in a quantified way robust solutions at strategic level. Simple ways of analysis include sensitivity and parametric analysis, varying the uncertain parameters. In particular market conditions will be subject to uncertainty, prizes and levels of demand.

To illustrate a strategic transportation model (simplified), consider the following variables and coefficients:

Variables

x_{it} = Hectare of area harvested in macro-stand i, period t
z_{jbt} = Volume (m^3) of product b, delivered at market j, period t
y_{irt} = Volume (m^3) of timber transported between macro-stand i, and plant r, period t
w_{rjbt} = Volume of product b, sent from plant r, to market j, in period t
h_{irt} = 1, if road-building (route) between macro-stand i, and plant r, period t, is built; 0 otherwise
Note: Some roads between macro-stand i and plant r already exist.
u_{rbt} = Volume (m^3) produced in plant r, of product b, period t

Parameters

c_{it} = Cost per m^3 of harvesting in macro-stand i, period t
p_{rbt} = Cost per m^{3}of producing product b, in plant r, period t
e_{jbt} = Revenue per m^3 of delivery product b, in market j, period t
f_{irt} = Cost per m^3 of transporting timber from macro-stand i, to plant r, in period t
g_{rjbt} = Cost per m^3 of transporting product b, from plant r, to market j, period t
q_{irt} = Cost of building road from macro-stand i, to plant r, in period t
d_{jbt} = Demand (m^3) for product b, in market j, period t
a_i = Total area (in hectare) of macro-stand i
m_{ir} = Capacity of road from macro-stand i to plant r
b_{rb} = Conversion factor: number m^3 timber to produce one m^3 of product b at plant r
k_{it} = Volume (m^3) per hectare of area harvested in macro-stand i, in period t

Objectives Max: Revenue – Costs

Revenue by sales $\sum_t \sum_j \sum_b e_{jbt} z_{jbt}$

Cost of road building $\sum_t \sum_i \sum_r q_{irt} h_{irt}$

Cost of harvesting $\sum_t \sum_i c_{it} k_{it} x_{it}$

Cost of transporting to plants $\sum_e \sum_i \sum_r f_{irt} y_{irt}$

Cost of production of plants $\sum_t \sum_r \sum_b p_{rbt} u_{rbt}$

Cost of transport to markets $\sum_t \sum_r \sum_j \sum_b g_{rjbt} w_{rjbt}$

Constraints

1. Timber production in macro-stand i
   $\sum_t x_{it} \leq a_i$ (Total area harvested in macro-stand i cannot exceed a_i)
2. Timber sent from macro-stand i to plant r through roads.
   $y_{irt} \leq m_{ir} \sum_{\theta=1}^{t} h_{ir\theta}$ For non-existing roads (ir) that needs to be built.
   $y_{irt} \leq m_{ir}$ For existing roads (ir)
3. All timber produced at macro-stand i in period t is sent to plants
   $\sum_r y_{irt} = x_{it} k_{it}$
4. Production at plant r in period t
   $\sum_i y_{irt} = \sum_b b_{rb} u_{rbt}$ (All timber is used to produce product(s))
5. Possible product b is sent from plant r to market j in period t
   $u_{rbt} b_{rb} = \sum_j w_{rjbt}$
   $z_{jbt} = \sum_r w_{rjbt}$ (Products arrives to markets j from any plant r)
6. Demand is bounded in all markets j for all products b in all time periods t
   $z_{jbt} \leq d_{jbt}$
7. All variables are non-negative, $h_{irt} \in \{0, 1\}$

The summation is done over all members of a set for each index used.

Management Planning in Action 8.1: Network Design Using Train Systems

Sveaskog is Sweden's largest forest owner and leading supplier of timber, pulpwood and biofuel. Some years ago, essentially all transports were carried out by logging trucks. At this time, there was a discussion whether the company should change the network to also use a train system taking pulp logs

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from southern Sweden to some large mills in middle Sweden and then move sawlogs from middle Sweden to several large sawmills in southern Sweden. Beside the decision to use a train system, decisions must be taken where to locate the terminals for loading and unloading. These decisions are very strategic but how is it possible to evaluate the possible decisions in a model?

It was decided to set up a tactical model where a set of potential terminals and train systems were used to define a number of scenarios. First, Sveaskog wanted to include binary decisions directly into the model. However, it turned out that to define the cost coefficients for the location of terminals and use of train systems required several weeks of negotiations, for each possible configuration (e.g. capacity). At this stage, it was decided to set up five main scenarios with given train system and configuration of terminals. Also, the actual costs of these scenarios were not known. However, each scenario had a fixed network so it would be possible to compute the annual cost of the transportation using a tactical flow model.

Map describing the area of the operations where the train system could make a difference. Red squares are potential locations of terminals, the main pulp-, paper- and saw-mills are illustrated with small factories and green arrows denote the forest areas. The five scenarios each included a set of terminals together with different configuration of the train system. This could for example be defined on the frequency of the train, its capacity and the number of locomotives in each system.

To provide information for the tactical model, information on all transports done the year before was available, and hence there was information on supply and demand. In total the case study had 1,500 supply points, 220 industries, 12 assortment, 5 assortment groups, 5 train systems and 10 potential terminals. The number of constraints was no more than 3,000 but the number of variables is 30 million. The reason for this is the fact that backhauling flows was allowed and they increases the number of variables drastically. The solution time for the scenarios ranged between a few minutes and several hours depending on the tolerance requirement.

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In the scenarios, it was clear that the transport by trucks could be reduced by 35 % and the overall energy consumption by 20 %. The latter also correspond to the decreased emissions of CO_2. Each of the scenarios provided the total cost beside the fixed cost for trains and terminals. However, when Sveaskog were doing the negotiations to establish these costs, it was very clear which alternative that would be the best scenario. However, in the end the total improvement in terms of cost was relatively small. Also, there were other concerns to consider. For example, if the train system was selected, it meant that 35 % of the truck drivers would not have any job and this in areas where the unemployment is high from start. The final decision was to start using the train system using one of the design scenarios.

8.4 Tactical Transportation Planning

At this level of decisions, the basic elements of the value chain, consisting of forests, primary and secondary plants, and roads are in place. Planning horizons ranges from around 1 month, a season to 1 year. The spatial configuration plays an important role, as locations and travel distances are important elements for the decision process.

The basic elements of decisions involve detailed definition of fleets, aggregated capacity level of trucks and other transportation means. This implies definition on how supply of timber at origins at the forest will be coordinated with demands at plants for timber, and processed products down the chain. Different transportation mode are used between forests and first destinations, plants, ports, stocking areas, and then between primary and secondary destinations. The main costs typically arise in the first transportation, between forests and primary destinations, so we will concentrate on this aspect.

A basic model (Epstein et al. 2007) to distribute timber is a simple transportation model, where at the origins supply is given by the expected harvest at stands and demands are given at destinations. Costs on each arc are defined by the unit costs of a back-and-forth transportation between each origin and destination. This is a simple LP model which gives an approximate solution to the distribution problem, an allocation of stands or catchment areas to specific destinations, and indirectly the fleet needed. If different assortments are defined, the problem can be transformed into a multi-commodity model and product substitution can occur by defining demand on assortment groups that could be satisfied by more than one assortment. Note the approximation taken in not considering explicitly the empty truck returns or queuing. Transportation costs are typically based on a full load from forest to mill, and then empty back to the forest. One main reason for this is that the volumes

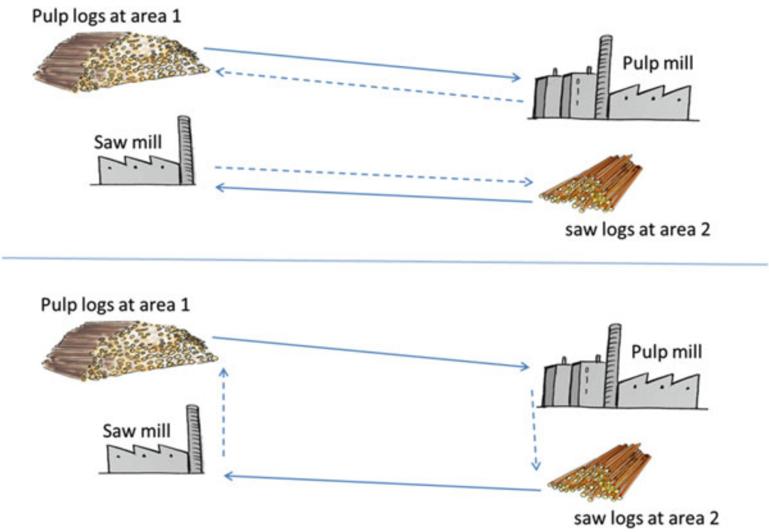

Fig. 8.3 Illustration traditional back and forward transportation (*top*) and backhauling (*bottom*)

available at harvest areas in forests are generally large and require several truck loads before it is empty. This implies that the loaded proportion is up to 50 %. Since most trucks need to drive from and to a home base in the beginning and end of the day, the loaded proportion is even more reduced. However, it is possible to generate backhauling possibilities where loads from two harvest areas are combined. This is illustrated in Fig. 8.3. In the basic version (top) the truck drives back and forward, and using backhauling (bottom) the truck drive the backhaul route: area 1 $\rightarrow$ pulp mill $\rightarrow$ area 2 $\rightarrow$ sawmill $\rightarrow$ area 1. Suppose the distance between areas and mills are 100 km and between pulp mill and area 2 (and sawmill to area 1) is 20 km. Then, the distance saved is 160 km which correspond to 160/400 = 40 %. It is evident that backhauling can improve the transportation efficiency. A model and solution approach based on column generation dealing with backhauling can be found in Carlsson and Rönnqvist (2007).

At his level of decision, more detailed information is required than at strategic level. Note here that spatial location of the timber production is relevant, as well as a clear definition of different types of timber and what volumes are produced. There is a need to have access to harvesting costs and transportation costs between stands and mills. In case the demand is not fixed, we need the market value of each product or assortment delivered to plants and/or customers. As inventory is important, we also need costs and capacities for holding timber at stocking yards or terminals and also wood freshness guideline.

Typical transportation situations have seasons when transportation is difficult. For example, in Chile, roads are made of gravel, which can be used year round and cheaper dirt roads, which cannot be used during the winter season due to rains. To make better use of the system, stocking areas, closer to plants and connected to

them via gravel roads are used to stock timber in summer for use in winter, as there is a need of a steady supply of timber to plants throughout the year. In a similar way, in Nordic countries such as Sweden and Canada, transportation is easier in winter when roads are frozen and more difficult in spring due to thawing roads. In this form, the use of inventories plays an important role in the yearly planning. We present a basic model which considers supply of timber known, demands as given, as well as transportation capacities and costs in all seasons, stocking yards costs and capacities. For the stocking yards, we consider the case of Chile, where timber is sent to stocking yards in the summer, and from the stocking yards to plants in the Winter. Since timber deteriorates, inventories at stocking yards must be sent completely to plants in the summer season. Periods will be defined by season, summer and winter.

For the sake of simplicity, we assume only one type of timber. In reality, multiple types of timber or assortments are considered, which can be exchangeable if allowed to downgrade. That is, wide diameter high value logs, normally sent to sawmill can be sent to the pulp mill, or even the energy mills. Opticort, a model representing this more complex reality is presented in Epstein et al. (1999a, b). Also for the sake of simplicity, we assume no capacities on roads. It is however easy to include such constraints. To illustrate a tactical model, consider the following variables and coefficients:

Variables

$x_{it} = 1$, if stand i is harvested in period t; 0 otherwise
$y_{ijt} =$ Volume (m^3) of timber transported from stand i, to plant j, in period t
$z_{irt} =$ Volume (m^3) of timber transported from stand i, to stocking yard r, in period t
$u_{rjt} =$ Volume (m^3) of timber transported from stocking yard r, to plant j, in period t
$v_{rt} =$ Volume (m^3) in inventory in stocking yard r, in end of period t

Parameters

$c_{it} =$ Cost of harvesting stand i, in period t
$e_{jt} =$ Revenue per m^3 at plant j, in period t
$f_{ijt} =$ Cost of transportation per m^3 between stand i, and plant j, in period t
$g_{irt} =$ Cost of transportation per m^3 between stand i, and stocking yard r, in period t
$h_{rjt} =$ Cost per m^3 of transportation between stocking yard r, and plant j, in period t
$b_{rt} =$ Capacity (m^3) of stocking yard r, in period t
$d_{jt} =$ Demand (m^3) of plant j, in period t
$a_{it} =$ Volume (m^3) in stand i, in period t
$l_{rt} =$ Cost for holding inventory in stocking yard r, in period t (per m^3)

Objectives Function: Max Revenue – Costs

Revenue: $\sum_t \sum_j e_{jt} \left(\sum_i y_{ijt} + \sum_r u_{rjt} \right)$

– Cost of harvesting: $\sum_t \sum_i c_{it} x_{it}$

- Cost of transportation from stands to plants: $\sum_t \sum_i \sum_j f_{ijt} y_{ijt}$
- Cost of transportation from stands to stocking yards: $\sum_t \sum_i \sum_r g_{irt} z_{irt}$
- Cost of transportation from stocking yards to plants: $\sum_t \sum_r \sum_j h_{rjt} u_{rjt}$
- Cost of inventory at stocking yards: $\sum_t \sum_r l_{rt} v_{rt}$

Constraints

1. Harvesting at stand i only once
   $\sum_t x_{it} \leq 1$
2. All timber harvested is transported to plants j or stocking yard r in period t
   $a_{it} x_{it} = \sum_j y_{ijt} + \sum_r z_{irt}$
3. Inventory at stocking yard r in period t
   $v_{rt} = v_{r,t-1} + \sum_i z_{irt} - \sum_j u_{rjt}$
4. Capacity of stocking yard r in period t
   $v_{rt} \leq b_{rt}$
5. Volume delivered at plant j must satisfy demand each period t
   $\sum_i y_{ijt} + \sum_r z_{irt} = d_{jt}$
6. $x_{it} \in \{0, 1\}$
   all other variables non-negative

8.4.1 Road Network Upgrading

In the strategic model, there were binary variables associated to use a particular link between forest and plant. This can be used to model both transportation mode and full roads availability. This is true when there is a need of new roads to access harvest areas. However, in many cases the roads do exists but may need to be upgraded to a higher quality. For example, a road may exist and it is possible to drive on the road during seasons of good weather conditions. But when the conditions are bad, the roads are not usable for transport. This is a typical situation in Sweden and Canada in the thawing period in the spring. The roads are then closed for a number of weeks. In order to cope with this situation, there are a few main alternatives. The first is to move logs to roads sites or terminals from where the logs can be transported without any problem. This gives rise to additional loading and unloading and hence extra cost and timber handling damage. The second is to use trucks equipped with central tire inflation (CTI) system where the air pressure can be controlled (e.g. lower

pressure to increase the area of contact between the tire and the ground) and hence the trucks can drive on roads impassable for trucks without CTI system. This is restricted to a few types of roads. A third alternative is to upgrade the roads so that they are not (or very limited) affected by the thawing.

Most of the models dealing with road upgrading, as well as building, are integrated with harvesting decisions (e.g. Andalaft et al. (2003)). These models have a medium term horizon but here we will focus on the decisions for road upgrading and harvest planning for the next year. However, in order to make the business decisions to be implemented, we need a methodology to analyze the impact of these business decisions. This can be done through anticipative planning where we include the behavior of other activities given the business decisions. For this reason, we include harvesting decisions over 5 or 10 years as anticipation variables (Frisk et al. 2006). With this time frame, we can guarantee more long term effects like keeping equal average distance from stands to mills, even harvest levels, etc. Moreover, we include industrial demand and the associated transportation flows as anticipation variables. As there are different requirements and restrictions over a year, we also divide each year into seasonal periods. None of the anticipation variables will be implemented in practice as they are only used to measure the impact of the business decisions. For example, transportation flows will be implemented in short term flow models on a monthly basis.

The upgrading problem requires detailed information on the roads and a GIS is required. Often there are many candidate roads or road segment that can be upgraded and the many roads give rise to a very large problem. This is particular true when the network flows are represented by nodes and arcs. This has been identified by e.g. Henningsson et al. (2007). In order to cope with the dimension, it is possible to generate a limited number of origin–destination routes. Thus, instead of using nodes and arcs, we can now use flows on routes which drastically can reduce the model size.

Management Planning in Action 8.2: Use of Backhauling in Decentralized Planning at Holmen Skog

Holmen Skog is a large Swedish forest company that manage more than 1.2 million hectares of productive forest land. The annual harvesting carried out within Holmen Skog is about 2.9 million cubic meters. Besides harvesting its own forest it also trade logs with private forest owners, forest associations and sawmills. Holmen Skog also co-operate with other forest companies. In 1999, Holmen Skog started to develop a web-based system Åkarweb [combination of Swedish word ‘åkare’ for truck driver/owner and ‘web’] to support the transportation planning carried out within the company (Eriksson and Rönnqvist 2003). The transportation work is carried out by a number of independent transport companies and organisations. The development

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focused on a number of issues. The purposes with the system were to enable efficient but decentralized planning that involves several transporters and companies. The actual information on supply, demand and inventories is given online. It also had a map support to show inventories and contact information on any transport order. A very important part was to identify backhauling opportunities between transporters even if it is the transporters themselves that make the decisions.

Backhauling is essentially improvement of two direct flows with different assortments from supply to demand points as illustrated in Fig. 8.3. The problem with backhauling is that the number of potential backhauls becomes very large. As a solution method it is critical to use column generation (Carlsson and Rönnqvist 2007).

During operation about 50 transporters associated with Holmen using the system. In addition there are 10 transporters associated with another forest company using it. In total there are about 180 logging trucks connected (direct or indirect through their transport planners). Once all information is collected each morning, an optimisation system solves a model to find the best possible backhauling trips. These trips are on a daily basis viewed by the users as a support for further planning. The system can be used both as a centralised and decentralised system, currently the latter is used. Given the potential backhauling trips it is then up to the transport planners to use them. This is a decentralised way to coordinate the transportation planning.

There is a number of potential savings using Åkarweb. There is considerably less administration with transportation management and the efficiency in the transportation increased. The experience show that the empty trucking distance for Holmen Skog (in the studied area) is in average 80 km per load. If the transports are optimized with respect to backhauling the empty trucking distance will be reduced with 15 %. The overall cost savings have been computed as 4 % in average. In the same study, interviews with hauliers showed that over 80 % of the users enjoyed working with Åkarweb. They believe Åkarweb simplifies and improves the transport planning and that it gives a good overview of the landings and helps navigation in unknown areas.

8.5 Operational Transportation Planning

Operational transportation decisions involve actual dispatching and scheduling vehicles to perform tasks. While other transportation modes exist, such as trains and barges, trucks constitute the main mode of transport by far, and models developed

have centered on them. The tasks are carried out by trucks of different types, differentiated by capacity, power of engine to have flexibility to carry logs of different dimensions and handle different types of difficulty in roads. Different types of trucks are used at different levels in the value chain. It is quite different to transport logs from forests to plants, then products from plants to customers.

As in the tactical model, we will concentrate on the first transportation leg, from forests to first destinations, which is where most of the effort in coordinating and gaining efficiency has concentrated. The most typical problem involves moving timber from origins at forest to destinations. This implies assigning trucks, which may be of different types to these tasks. There are basically two modes of hauling. In one case, trucks go back and forth from origins at forests where they are loaded in one origin with timber which need to be delivered at one destination. This is the case of forests in Chile, South Africa and other countries, where large companies own forests, so the volume at origins is enough to fill trucks. Alternatively, trucks follow a route, collecting timber at different origins and delivering at one or more destinations. This is a typical case of Sweden for example, where timber is produced by small owners, who deliver high value, smaller volumes of timber, and several owners need to be visited to fill trucks. Different models have been proposed for each case. Note that in the case of back and forth trips, the whole day travel of a truck can be defined as a route, alternating between pick up points and deliveries at destinations.

The Vehicle Routing Problem (VRP) in timber transportation is quite different from standard VRP problems found in the literature. Audy et al. (2012a) report a number of attributes that distinguish a PDP in timber transportation from a more general PDP. VRP in timber transportation is a variant of the *pick-up and delivery vehicle routing problem*, more commonly designated a *pick-up and delivery problem* (PDP). Mills and stands may have particular times available for delivery and pick-up and we have so-called time windows. When time windows are used, the problem is called a VRP with Time Windows (VRPTW).

In their classification scheme for PDPs, Berbeglia et al. (2007) differentiate three *structures* to describe the number of origins and destinations of the commodities involved in the PDP. Two of them can be seen in timber transportation depending on whether the supply and demand points are paired (i.e. *one-to-one*) or unpaired (i.e. *many-to-many*). The structure *many-to-many,* in which any site can serve as a source or as a destination for any commodity and the structure *one-to-one,* in which a commodity has a given origin and a given destination. This means that in the *many-to-many* structure, the PDP includes allocation decisions (i.e. which supply points satisfy which demand points in what volume of a given product) in addition to the truck routing decisions. With reference to both structures, we provide a general description of the main attributes defining PDP in timber transportation. In a PDP in timber transportation, a set of vehicle routes must be generated in order to deliver a set of *requests* (one-to-one structure) or to satisfy a set of *demand points* (many-to-many structure) according to a given objective (e.g. total minimum cost and/or total minimum empty driving distance) and subject to a set of constraints. A *request*

specifies a volume, an assortment, the site where it is to be picked up (origin) and the site where it is to be delivered (destination). Time constraint(s) can be added onto a request (e.g. a latest delivery time or a time window when the pick-up must be made). A *demand point* is a location requiring specific volume in an assortment group (defined by one or several assortments). To satisfy the set of demand points, a set of *supply points* is available; each supply point is a location that can provide specific volume in an assortment. Both the origin/supply and destination/demand sites can be visited more than once. This is the typical situation as the volume available usually exceeds one truckload. On a planning horizon over a day, the entire demand can be divided into daily minimum and maximum accumulated volume, while the entire supply can be released into daily volume. This allows spreading out the deliveries/pickups at a demand/supply site over the whole planning horizon and, for the latter, representing a daily production (e.g. by a harvest team) at supply site. Transportation priority can be put on e.g. certain urgent requests to deliver or critical supply/demand points to empty/fulfil.

To execute the transportation, a fleet of vehicles is available. This fleet of vehicles may consist of the same (homogenous) or different (heterogeneous) vehicle types, each with a unique set of transportation-relevant characteristics (e.g. capacity, set of assortments allowed to haul, fuel consumption, trucks with or without a crane, set of sites not allowed or impossible to visit). The vehicles are spread throughout a set of sites (multi-depot) or based in only one site (single depot). A route usually starts and ends at the vehicle's depot. For a planning horizon exceeding 1 day, the vehicle may be allowed to come back to the depot (or home base) not fully unloaded (i.e. stay loaded overnight), in which case the delivery must be performed the following day. Multiple pickups may be necessary before the truck is full, which is the typical situation when the harvesting is finished and there is a need to clean off all piles, including some with less-than-truckload size. To fill-up the truck, some piles are subject to a partial pick-up and this complicates the planning process. Different approaches are used to deal with this; most are heuristic based.

A route must respect different time constraints such as vehicle's working hours availability (e.g. to disallow working at night), length of driver's work shift, time windows at supply/demand points, etc. More than one driver's work shift could be scheduled on a vehicle. The change of driver can be performed from among a set of predefined changes over sites or only at the truck's depot. Time windows at supply/demand points consist mainly of two forms: opening hours and on-site loader(s) operation hours. The first specifies the site's opening hours in which a vehicle can perform a pickup/delivery, while the second specifies the hours in which on-site loader(s) are available for (un)loading operations. Vehicle types without crane must be scheduled inside both time windows at any site while usually, vehicle type with a crane (i.e. self-loading) must be scheduled inside both time windows only at delivery site. Waiting time is generally allowed when a vehicle arrives before the beginning of a mandatory time window and waiting time for vehicle queuing can also be computed (e.g. when a vehicle waits for a loader already in use by

another vehicle). Rather than specify predefined time windows for on-site loader(s) operation hours, the PDP can also include the scheduling of on-site loader(s). We refer to *multiple time windows* (as in Xu et al. 2003) to designate e.g. the site's daily opening hours that can change according to the day of the week. It is also possible to address queuing of trucks at mill gates, which is typical for large industries with several specialized production lines. In such a case, it is necessary to come up with a good queuing strategy in order to minimise the waiting time in the industry's yard as well as to minimise additional movements in the yard transportation from log-piles to productions lines. An approach based on revenue management principles has been tested in a Portuguese pulp and paper mill by Marques et al. (2012) and this is described in detail below in Management Planning in Action 8.3.

To solve PDP in timber transportation, several planning methods have been proposed in the literature. In the next section, we review a number of solution methods and refer to Audy et al. (2012a) for a exhaustive review.

Linnainmaa et al. (1995) propose a three-phase approach using exact mathematical programming methods and heuristics to generate a weekly truck schedule. Weintraub et al. (1996) propose a simulation-based method described in Management Planning in Action 8.3. A column generation method in which each column corresponds to one feasible route is proposed by Palmgren et al. (2003, 2004) and Rey et al. (2009) to generate a daily truck schedule. McDonald et al. (2010) propose a simulated annealing method in which each new solution (daily routes schedule) generated is evaluated according to four performance metrics. Gronalt and Hirsch (2007) and the third phase of Hirsch (2011) propose a Tabu Search (TS) method to generate a daily route schedule to deliver a set of requests. Flisberg et al. (2009) also propose a TS in the second phase of their method generating routes schedules for up to 5 days. With Rummukainen et al. (2009), Flisberg et al. (2009) propose the two planning methods that support the consolidation of less-than-truckload (LTL) size requests in full (or nearly) truckload-size request. Rummukainen et al. (2009) propose a three-phase method embedding a mixed integer programming (MIP) model, a dynamic programming algorithm and two TS heuristics. El Hachemi et al. (2009) and El Hachemi et al. (2011) propose a two-phase method to solve consecutive daily PDPs from an initial weekly PDP. The first method embeds local search algorithms enhanced with a tabu component and a greedy heuristic. The second method embeds an MIP model and a constraint-based local search model with two solving approaches: an iterated local search algorithm and a hybrid algorithm combining previous iterated local search algorithm and constraint programming.

The availability of information at planning time is an important dimension present in PDP. In *static* problems, all information is assumed to be known a priori, while in *dynamic* problems, information is revealed gradually and/or subject to change over time. Nearly all papers in the literature on VRP in timber transportation address static PDPs, while Rönnqvist and Ryan (1995) and Rönnqvist et al. (1998) are exceptions by proposing a truck dispatching solution method for a dynamic PDP.

However, it is critical to be able to anticipate the future and make a full day plan that can be changed later. A key component for such a system is to be able to re-optimise given a current partial solution. Also, the information handed back to each truck's driver is usually only information about their next trip, as their expected planned route may change after a re-optimisation. To allow decision maker in timber transportation to use computer-based routing methods, decision support systems (DSSs) embedding the planning methods have been developed and deployed in the industry. Audy et al. (2012a) discuss a number of DSSs in timber transportation, including ASICAM discussed below, RuttOpt in Sweden (Andersson et al. 2008) and VTM in Canada (Audy et al. 2013).

Management Planning in Action 8.3: ASICAM, a Forest Truck Scheduling System

ASICAM is a simulation based computational system used successfully by forest firms in Chile and other countries. Traditionally schedules were generated manually, where to simplify the problem, each truck always traveled between one origin and one destination, with no timing considerations. In addition to the loss in optimality due to the manual scheduling, since it took a long time to develop a schedule, it was used through a week or longer. Obviously, since supply and demand for specific logs change every day, a rigid schedule could not lead to good solutions in different days. The consequences of the manual planning were deficient schedules. Demand for some logs could not be satisfied, there was friction among the drivers who competed to do more trips, there was poor coordination with downstream operations and, mainly, the transportation costs increased specially as trucks had to queue for long times due to congestion both at origins and destinations. In 1989, the firms, who had organized a center for innovation jointly through a consortium, asked us to develop a system to improve the truck scheduling. The basis for the system was organizational, a central office planned all trips (origin, destination, time of departure, and since the travel time is known, time of arrival to destination), and the use of a system to schedule the trips. It was based on simulation with heuristics. The model works by time increments (see below Figure). It starts at 6.00 am when the first trucks are being loaded at origins, at 6:20 am the trucks leave for their destinations, to which they will arrive at 6:20 plus the travel time (TT) required. At 6:20 plus TT plus 20 min the trucks are empty ready to travel to a new origin. At 6:20 a second batch of trucks starts being loaded at origins, and leave loaded at 6:40 am. In this form the model advances through the day, traveling between origins and destinations. Note that if a truck reaches an origin or destination with trucks ahead of it, it has to queue. The planning horizon ends at 6 pm, when the transportation system is stopped, or longer if there is overtime. Periods

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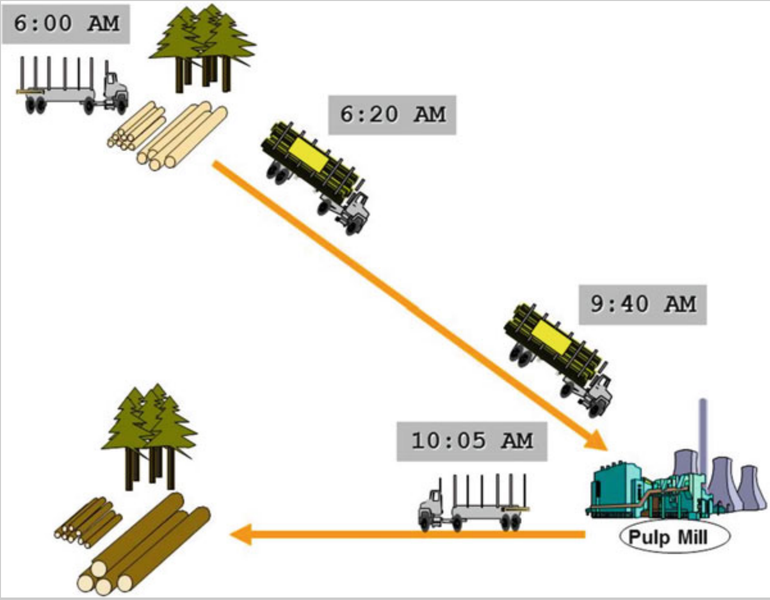
were defined of 20 min each, corresponding to loading, unloading time. Travel times were approximated to these 20 min periods.



The simulation needs to take into consideration: demand and supply for each type of log at each node, availability of trucks and cranes for loading, unloading times and costs for all activities. There are multiple constraints where the main ones are: demand for each log type at each node, arrival of logs at destinations should be steady to make downstream operation easy, a number of organizational issues must be included, such as lunch breaks, drivers starting and ending their day near their homes, have similar incomes for all trucks in each week, etc.

The main challenge was to find heuristic rules to assign trucks once they become empty. The rules need to consider the constraints as well as minimizing costs. The model considered a horizon of 1 h, to be able to schedule multiple trips jointly, but only implemented the first period of 20 min. A desirability index for each trip was calculated as the real cost of the trip (including queuing) plus a congestion cost, derived by queuing caused to other trucks. Priorities of trips were defined, the main one to fulfill the demand for each log type at each node. Typical forest operations carry out between 100 and 700 trips per day and need between 40 and 250 trucks. The system runs in a few minutes on a regular PC. It is typically run early in the afternoon and the instructions are sent to the drivers by email. There are unexpected events

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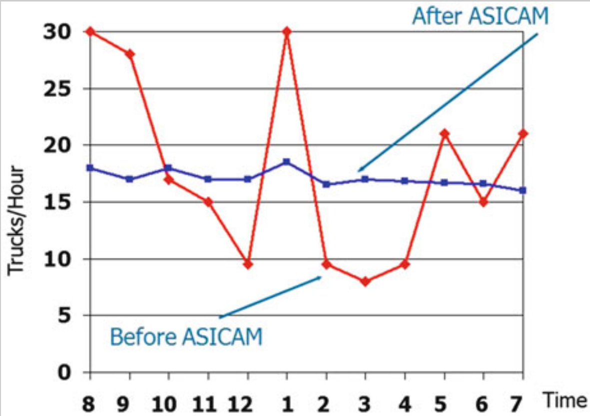
during the day, such as breakdowns of cranes, which are handled manually, via radio, by the operators. The system was implemented by all major forest firms in Chile, very successfully. Costs were reduced between 15 and 25 % and the number of truck even more. Average queueing was reduced from 4.5 to 0.5 h. Below the Figure shows how the arrival of trucks to destinations became much more steady.



The system was also used by forest firms in South Africa (MONDI won the South African Logistics prize 1996 using ASICAM), Brazil, Uruguay, Venezuela, Argentina. ASICAM, with upgrades is being widely used. ASICAM, with other operational systems, won the INFORMS Edelman Prize Competition in 1998 (Weintraub et al. 1996).

8.6 Real Time Operations – Wood Reception Planning

The timber harvested in industrial plantations is transported by truck directly to the mills or to intermediate stockyards where it may be temporary stored and then transported to the mills. The reception of the wood at the mills and stockyards has been poorly addressed in the literature. Transportation planning is often conducted without taking into account the trucks arrival and entrance at the mill, unloading and internal movements until exiting the facilities. However, during the delivery day, the wood trucks are confronted with congestion and queuing for loading at the harvesting sites and for unloading at the mills. There may be hundreds of trucks arriving at the mill each day, coming from neighboring harvesting sites, with similar schedules and travelling identical routes to the mill. In some cases unloading at

the mill during certain rush hours (close to lunch time and at the end of the day) may take up to 4 h when the estimate duration is 40–50 min in non-congestion conditions (Marques et al. 2012). Congestion and queuing particularly at the mill's gate increases the duration and costs of the transportation services and decreases the efficiency of the reception process. Increasing concerns about truck waiting time can be noted in the recent literature with the development of a few routing methods aiming a better coordination with the scheduling of the loading equipment.

In most of the mills, the main decisions related with wood reception planning are taken by the mill receptionist that deals with sequencing the trucks when they actually arrive at the mill's gate and decides its best unloading location. The arrival of the trucks is not known beforehand. Wood reception is often conducted independently from mills production processes. Consequently, the trucks enter the mill on a First-In-First-Out (FIFO) basis according to their arrival time and mainly unload at an active cell of the stockyard. Consequently, other transporters are needed to move the stock to the production lines assuring its continuous operation.

More sophisticated wood reception planning processes may occur when the set of trucks arriving at the mill each day is known beforehand (Marques et al. 2012). The harvest manager may provide information about the trucks expected to departure from each harvest site and destined for the mill. In this case, wood reception planning starts during tactical transportation planning for establishing optimal schedules for the planned trucks in order to avoid congestion.

This decision problem relies in the discretization of the mills opening hours into time slots and consists in assigning the planned trucks to the available time slots, assuring that the arrivals are evenly distributed along the day. The assignment problem may take into account a priority index that reflects the relative importance of each truck. This index may be built upon the historical behavior of the carrier/truck over the last deliveries, its number of next scheduled trips for the same day and/or the freight/truck specific characteristics. The minimum cost assignment problem may foresee a set of time slots that should be used by the unplanned trucks that will arrive at the mill each day carrying market wood.

The time slots assigned to each planned truck should be communicated to the carrier. The transportation contract should foresee benefits for arriving within the reserved slot, which may include reduced waiting time. Such sophisticated wood reception planning processes may further improve the decisions of the mills receptionist during the delivery day. Therefore, the sequence of the trucks may be set according to the previously established priority index and the compliance with the planned schedule.

The wood reception planning process may be integrated with the wood supply to the production lines. The trucks may preferentially unload directly at the production lines, therefore reducing the number of freights coming from the stockyard. Thus, match between the wood assortment carried by the truck and the assortment consumed at the production line is of great importance during the assignment process.

The wood reception problem was firstly presented in Marques et al. (2012). The authors propose to approach this problem with Revenue Management (RM) techniques (Phillips 2005; Quante et al. 2009; Talluri and van Ryzin 2004). The proposed technique consists in classifying the trucks/carriers into priority segments and progressively assigning them to time slots at the gate and at the unloading location, currently available for its segment. This approach was implemented in a three-phase method that runs in distinct time frames.

Before the delivery day, Time Slot Allocation Planning (Phase 1) finds the best time slot/unloading docks for the planned deliveries, minimizing the overall daily reception extra-cost. It acknowledges both the cost of materials handling at the stockyard (i.e. related with the internal stock movements from there to the unloading dock at the line) and the cost of having the trucks stationary inside the mill. Consequently, the direct unloading at the production lines is prioritized.

During the delivery day, the time slots reserved are kept available as long as possible. Each time a truck arrives (planned and unplanned) the Time Slot Order Promising (Phase 2) assigns the truck to the best time slot/unloading dock that are available for its segment. Planned trucks arriving on-time have direct access to the mill. Delayed trucks in higher segments will have a large range of slots available, therefore will have lower waiting time.

Nevertheless, just before starting the time slot at the line, Time Slot Order Allocation (Phase 3) selects the best truck in queue according to the minimum cost criteria. Consequently, if the slot was still reserved for a higher priority truck, it will be assigned to another truck waiting in the queue. The daily delivery schedules obtained with the three-phase solution method were compared with the results of the FIFO approach used today. The daily wood reception costs were reduced in 55 %. Significant reductions were also reported for the maximum waiting time to unload, particularly for the trucks within higher priority segments.

Management Planning in Action 8.4: Wood Reception Planning

The pulpwood reception at a pulp mill was studied by Marques et al. (2012). The case study was based on data from the pulp and paper mill Europac Kraft Viana at Viana do Castelo from the EuroPac Group, located at the northern region of Portugal. The mill produces since the 1980s Kaftliner paper for packaging, using Pinus pinaster and Eucalyptus globulus pulpwood as well as recovered paper. Its annual production rounds up 350 thousand metric tons of paper, consuming about 700 thousand metric tons of maritime pine and 180 thousand metric tons of eucalyptus pulpwood. The majority of the pulpwood comes from the national market. Only a small fraction is produced in self-managed forests. The wood reception at the mill is often conducted without planning in advance. Yet, an average sized pulp mill can receive more than

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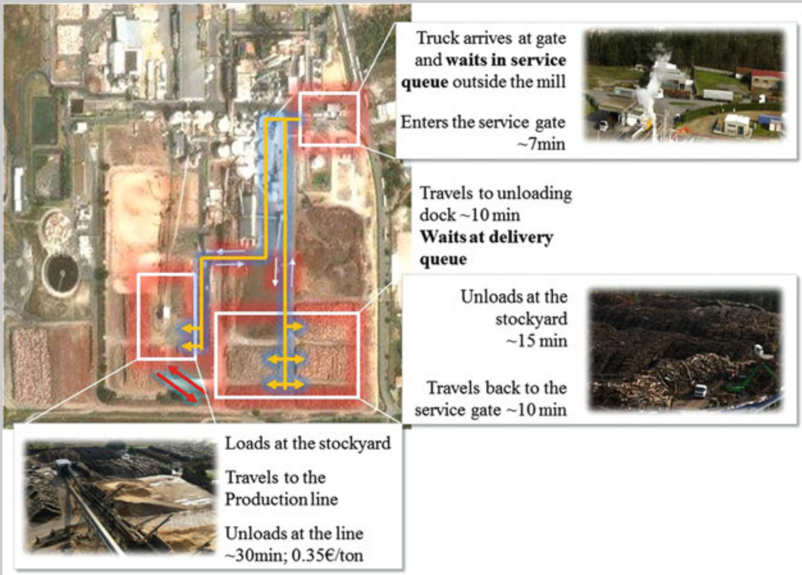
120 trucks per day. Total waiting time of over 4 h was reported for trucks arriving during rush hours (9–11 am, 11 am–01 pm and 7 pm–9 pm).

The problem instance included 120 trucks (72 planned and 48 unplanned). Each truck carried one log assortment, consisting in barked or unbarked logs of different volume and density. Their maximum tonnage is limited by national regulation to 40 ton or 60 ton (about 28 or 48 ton of payload). Three distinct wood assortments and six possible unloading docks inside the mill were considered. The time was divided into 496 time slots.

The wood reception process at the mill may be represented by the wood flows over the mill layout. The truck arriving at the mill is placed at the service queue, where it may stay for several minutes or even hours. The operations at the service gate take less than 10 min. The load is weighted and the reception manager decides the unloading location. It can be the stockyard or directly at the production lines. Unloading operations often take only take 10–15 min using a stationary electric crane. When empty, the truck exits on the same gate where a new weighting estimate is recorded. The supply stage assures the continuum operation of the production lines during 10–14 h per day. The line includes an unloading table connected to a rolling runway that forward the pulpwood to the log feeders, where the wood will be mechanically barked and chipped.



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The proposed solution approach based on Revenue Management principles reduced the queuing effects and led to a 55 % reduction on the daily reception extra-cost for one delivery day at the Portuguese pulp mill, when compared with the FIFO procedure used today. Both the total waiting time to complete the reception process and the materials handling cost were reduced. This method further accomplished the reduction of the waiting time for both the planned deliveries arriving on-time and the trucks with higher priority index.

The implementation of this solution approach in the Wood Delivery System prototype enabled the generation of several "what-if" scenarios, those comparative analysis provided valuable information to design ad plan the reception process under both the carrier's and the mill's perspectives.

8.7 Open Questions and Future Research Guidelines

One key issue for transportation planning is the uncertainty. Even if most models are based on deterministic models there is a need to take into account uncertainty. On a strategic level, the volumes available in the stands are uncertain depending on the growth model and their uncertainty. However, at this aggregated level, it will not impact feasibility as this can be dealt in later tactical and operational models. At strategic level there is also uncertainty about future economic and market variables which may impact decisions taken. For example, sharp increase in oil price or new environmental constraints which compel to change structural options. On a tactical level, the uncertainty can be dealt with keeping a safety stock available either at stands or terminals. Also, it is possible to make sure that the average distance is kept throughout the planning period in order to enable that the transportation capacity is not limited in some periods. On an operational level, it is possible to include also safety stocks or to include extra times to consider uncertainty when deterministic travel times are used. Even if there are ways to cope with uncertainty it will be one of the challenges in the future to improve the planning capability using either stochastic programming and/or robust optimization.

There is a lack of methods to deal with real time operations. Such models will require more information that is updated in real time. Furthermore, the models must include synchronization with loading and unloading as well as considering the queuing issues. Finally, the topics of collaboration between the agents of the wood supply chain are still seldom addressed in the literature. New collaboration strategies and collaborative business models may introduce new objectives and constraints to the existing transportation planning problems (e.g. Audy et al. 2012b).

8.8 Summary

In this chapter, we have described the differences between strategic, tactical and operational transportation planning. As described in Chapter 7, transportation planning is often used to enhance other models. The strategic models often deal with designing the network and transportation mode selection. Hence, such models naturally involve many binary variables. The tactical models are more concerned with allocation rules i.e. how to connect supply and demand points. Important for such models are also seasonality which implies that inventory management is an important aspect. The operational planning typically involves routing and the size of the models increases dramatically. Even more difficult with data and optimality is real time planning as e.g. described for the wood reception problem. In the strategic and tactical models it is often possible to solve them to optimality. This is due to the fact that they are often aggregated and limited in size and the fact that the solution time does not need to be very quick. For the operational models, it is often necessary to develop various heuristic approaches. It is also important to note that these models are often different based on the characteristic of the company and or country.

8.9 Problems

1. Describe how backhauling can be included in tactical transportation planning. List different alternatives in how to generate backhauling routes.
2. Describe which characteristics that will provide different routing problems for forest transportation.
3. Describe and suggest a model when truck transportation and train systems are integrated. In particular suggest how to model the train system with its possible characteristics.
4. Propose a model formulation for including queuing in the routing problem.
5. Describe how different objectives can be included in strategic, tactical and operational planning.

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